Chapter 9

Damage Mechanisms in the Handling of Fruits

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Introduction

The recognition of an increasing and worldwide demand for high quality in fruits and vegetables has grown in recent years. Evidence of severe problems of mechanical damage is increasing, and this is affecting the trade of fruits in European and other countries. The potential market for fresh high-quality vegetables and fruits remains restricted by the lack of quality of the majority of products that reach consumers; this is the case for local as well as import/export markets, so a reduction in the consumption of fresh fruits in favour of other fixed-quality products (dairy in particular) may become widespread. In a recent survey (King, 1988, cited in Bellon, 1989), it appears that, for the moment, one third of the surveyed consumers are still continuing to increase their fresh produce consumption. The factors that appear as being most important in influencing the shopping behaviour of these consumers are taste/flavour, freshness/ripeness, appealing look, and cleanliness.

Research on mechanical damage in fruit and vegetables has been underway for several years. The first research made on physical properties of fruits was in fact directed towards analysing the response to slow or rapid loading of selected fruits (Fridley *et al.*, 1968; Horsefield *et al.*, 1972). From that time on, research has expanded greatly, and different aspects of the problem have been approached. These include applicable mechanical models for the contact problem, the response of biological tissues to loading, devices for detecting damage causes in machines and equipment, and procedures for sensing bruises in grading and sorting.

This chapter will be devoted to the study of actual research results relative to the cause and mechanisms of mechanical damage in fruits (secondarily in vegetables), the development of bruises in these commodities, the models that have been used up to now, and the different factors which have been recognized as influencing the appearance and development of mechanical damage in fruits. The study will be focused mainly on contact-damage – that is, slow or rapid loads applied to the surface of the products and causing bruises. (A bruise is defined as an altered volume of fruit tissues below the skin that is discoloured and softened.) Other types of mechanical damage, like abrasion and scuffing, punctures and cuts, will be also mentioned briefly.

The incidence of mechanical damage

Harvesting, post-harvest handling, packing, transportation and distribution of fruits and vegetables involve numerous mechanical operations and much impact-related flesh bruising. Impact has been recognized as the most important cause of damage (bruising) in fruits. Excessive compression also causes bruising, as do repeated impacts.

The apple is one of the most problematic fruits in relation to mechanical damage. It has also been extensively studied, and some data have been gathered on the percentage of fruits that are bruised during harvesting and grading. It can be as high as 81% of bruised apples during harvesting, 93% after transporting, and 91–95% caused by bagging (Timm *et al.*, 1989), all using manual harvesting systems.

In a study recently made in the Danish market (Kampp, 1990), it was established that only a few of the examined fruit samples met the EC quality standards for the products studied: 18 varieties of apples, and different numbers of varieties of strawberries, carrots, peaches and nectarines. In the retail samples, more than 20% of the strawberries had pressure damage; 20% of the examined peaches and nectarines had pressure or impact damages; and about 95% of the apple samples did not comply with the EC standards for bruises, 55% of the apples having 1–6 bruises per fruit. In addition, it was observed that some of the produce was being sold unripe, having been harvested at too early a stage.

In Spanish production of fruits and vegetables, quality control is being applied by a leading group of commercial companies (Valenciano García, 1990). Apple and pear samples were examined at retail stores; bruise damage was responsible for 50% of the total damage observed (which amounted to 23–35% including diseases, peel, shape, size, peduncle, etc.). In pears, 10–25% of the observed total class-rejection damage was due to bruises. Other products studied included strawberries, lettuce and green peppers. In the case of strawberries, nearly all damage was caused in the field, and was related to overmaturity of the fruits. Iceberg lettuce showed 5.5% bruise damage (from a total damage of 6.5%). In the case of green peppers, 8.5% of the product showed mechanical damage, most of it being caused during field harvesting and transporting processes within Spain (Ruiz Altisent, 1990, unpublished data). Data obtained in some onion grading plants showed that a high proportion of the product is being rejected from the highest-quality (export) class, amounting to 25–35%; similar figures are observed for potatoes. All these results mean there is a real need to improve the systems and the products to avoid very high economic losses from quality reduction and actual product losses. Expert systems are being applied to solve these problems.

Consumer safety is one of the main concerns of agricultural R&D. From some data gathered during recent years in the European fruit markets, we know that some retailers base their profit on high-quality, high-price fresh fruits and vegetables. This is attained by applying a very strong selection for 'extra-fancy' quality that causes a very high proportion of rejects. These are then sold in second-class more economic retail markets. This situation raises the question of safety and value to the consumers in these markets. Efforts to ensure a high quality of fresh fruits and vegetables are being made worldwide.

Causes of mechanical damage

Bruising appears as a result of impacts and compressions of the fruits against other fruits, parts of the trees, containers, parts of any grading and treatment machinery and on any uncushioned surfaces. Severity of damage to the fruit is primarily related to: (i) height of fall; (ii) initial velocity; (iii) number of impacts; (iv) type of impact surface and size; and (v) physical properties of the fruit, related or not to maturity.

Fruit that is marketed to be consumed fresh is harvested manually. This means that fruits are picked one by one by hand-pickers and placed into some type of containers, then transported to a packing-house in different types of vehicles (trucks, tractors plus trailers). There, fruits are subjected to a number of operations, which vary greatly between commodities, but which combine similar individual treatments. Table 9.1 shows a list of such operations, and a combination of these is made up for the different species; it is important to state that any combination of treatments may be applied to freshly picked fruits and also to stored fruit, at shorter or longer periods of time after harvest; also, the last operations, transportation to wholesale and retail, may add up to various cycles (two, three) as the product proceeds from production site (a different country in export operations) to retail market. This will create important differences in the damage that is caused to the fruits, due to the significant changes which may occur in their physical and physiological properties, related to variations in time lapses and environmental conditions. Also, transportation/storage/grading may have to be combined with a cooling chain; the maintenance of this whole system is of

Table 9.1. Harvesting and handling operations used in fruit marketing.

Harvest into:
- buckets
- field-boxes, or
- pallet boxes

Transportation to packing-house
Dumping, dry or into water
Washing
Waxing
Sorting
Sizing
Packing
Cooling
Storing
Transportation to:
- wholesale markets
- chain store distribution centres
- retail markets

Shelf storage

great significance in the changes of the mentioned fruit properties, and therefore in their susceptibility to damage at any stage.

It appears that most of the studies on damage caused to deciduous fruits have been carried out in relation to mechanical harvesting, as this is the main concern in the design and in the adoption of this type of equipment, for industry as well as for fresh market fruit. Diener and Fridley (1983) emphasize the importance of pruning to avoid excessive impacts of fruits against limbs during their fall through the tree, when harvested by the shake–catch method; canopy shapes are recommended. Other innovative procedures for catching the fruits without submitting them to drops have been investigated, as well as special padded-roller conveyors for minimizing impacts on the fruits during in-field handling. Today, no mechanical harvesting is used for fresh market fruits, but some of the conveying devices have been introduced in fruit grading machines. They consist mainly of padded rolls which feed the fruits instead of letting them fall between conveyors; they eliminate the drop-height and acceleration to the fruit, thereby eliminating impact.

Cushioning of the catching surface of a harvester is supposed to eliminate bruising. Zocca *et al.* (1985) report the results of shake–catch harvesting of two varieties of apples and one of peaches. The catching surface was covered by a well-cushioned PVC material. Thirty percent of the fruits were bruised in the case of peach variety Babygold 9; 50% and 63% in the case of apple varieties Abbondanza and Renetta Grigia. This result shows the different susceptibility to impact by different fruits (lower for peaches than for apples), and also the high impact damage applied to the fruits by this method of

harvesting. Similar results have been obtained during recent years by other authors working with different varieties of apples (Bilanski and Menzies, 1984). Bennedsen (1986) used special 'X' and 'L' shaped foam shapes mounted on the catching frame. Laboratory tests indicate that only 8–11% of the apples dropped on this catching frame were damaged.

Bruising could be maintained at a level of 2–7% in Granny Smith apples when the orchard was 'H'-shape-canopy-trained and the cushioned catching frame could thus be positioned immediately below the fruits. Using the same canopy training in raspberries, machine-harvested berries were of excellent quality (no damage) when harvested with a rotating-finger harvester (Dunn *et al.*, 1976). Commercial tomato varieties may be dropped as high as one metre without damage.

These results show clearly that different species of fruits (and varieties within species) will react very differently to similar damaging inputs when harvested or handled. This leads to some conclusions on impact damage mechanisms, some of which will be studied further.

Recent studies show a renewed interest in introducing mechanical harvesting of fresh market Golden Delicious apples (Peterson and Miller, 1988). An impact shaker and a rod-press harvester were able to pick up to 95% of the fruits with an average of up to 90% extra fancy/fancy quality. Burton *et al.* (1989) made studies to quantify and identify the areas where damage occurs to apples during bin filling and handling, and during transport to the packing-house, with the aim of introducing improvements in the whole system. The importance of using well-damped suspensions on the trucks and a cushioning lining in the bins was emphasized for long-distance transportation (50–500 km). Relative to transportation, Schulte Pason *et al.* (1989) show the strong relationship between distance of travel, degree of apple bruising and number of impacts greater than 20 g as determined by an IS (Instrumented Sphere, also called SEP: Simulated Electronic Product). A recent development of these SEPs, impact data acquisition units, makes it possible to study fruit harvesting and handling equipment for the level of damage applied to the products, as well as the specific damage sites (Nissen and Kampp, 1987; Anderson, 1990).

Fruits may be classified into different types regarding their most evident physical properties, which are responsible for their susceptibility to bruising. Such a classification is very inaccurate, as many fruits may change from one type to another during ripening or when subjected to different conditions. Nevertheless, some groupings may be made.

Firstly, one may distinguish between 'rigid' ('hard') and 'liquid' ('plastic' or 'soft') fruits (Fig. 9.1).

- Rigid fruits are those whose strength is based on a mostly rigid structure, surrounded by a thin elastic skin: apples, pears, peaches, nectarines, apricots, avocados, mangoes, papaya, kiwi fruits, potatoes, etc. In this

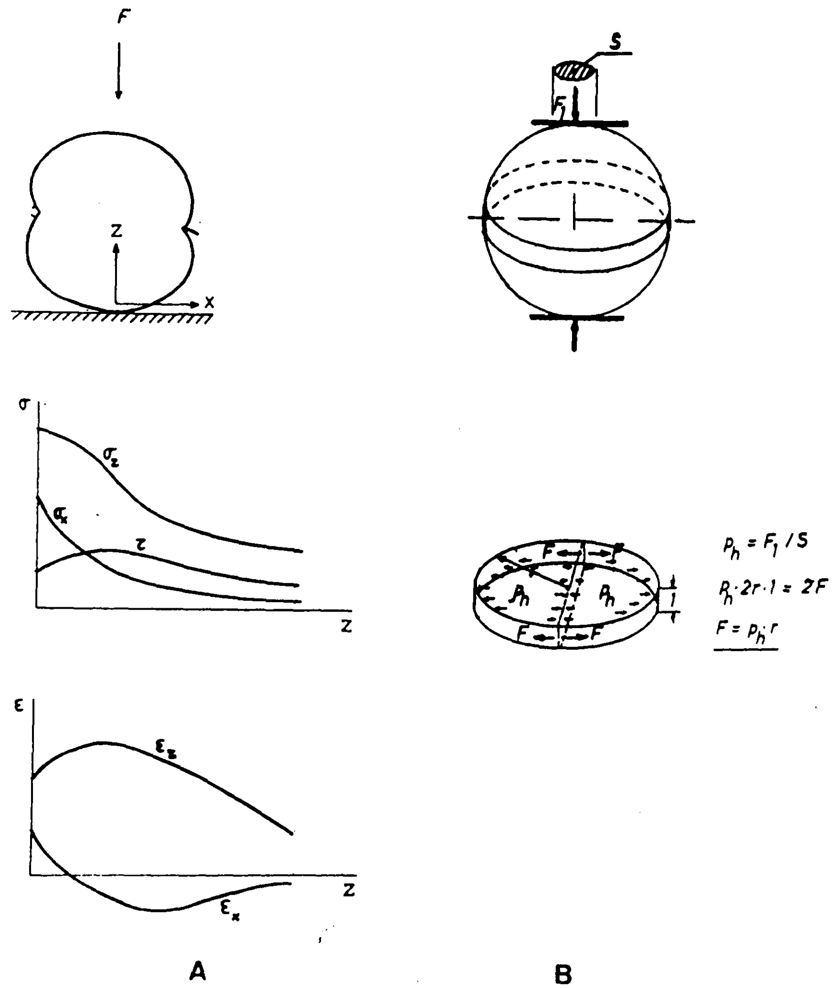


Fig. 9.1. Fruits can be considered as elastic solids (A) or as liquid-filled elastic spheres (B) (Ruiz-Altisent and Gil, 1979); these mechanical models are extreme approximations to real fruits (p_h – hydrostatic pressure; F – force exerted to the skin due to p_h; (see also Table 9.2).

type of commodity resistance is based in the fruit flesh, in its histological and physiological characteristics mainly.

- Liquid fruits are made up by a liquid or 'soft' mass contained in a mostly elastic skin, their resistance being based on this skin: examples include plums, tomatoes, grapes, cherries and berries. It is known that many rigid fruits gradually become soft as they mature.

- Mass of the fruits is crucial in bruising susceptibility, since impact energy is, as known, directly dependent on the dropping mass. Small fruits will be handled much more safely than large fruits.
- Thick-skinned fruits, like melons, water-melons and bananas are very resistant to impacts, but skin rupture problems may occur with these fruits.
- Fibrous fruits like pineapples react in a very different manner to impacts, and have not been widely studied.
- The stone in fruits is the cause of internal bruising for higher-energy impacts in some fruits and varieties.

All these different types of fruits will have to be studied accordingly when trying to describe and to model their behaviour.

External damage of the fruit skin can be caused by friction and abrasion against bin walls and conveyors. Oranges are especially susceptible to this type of damage (Chen and Squire, 1970; Juste *et al.*, 1990), as are other citrus fruits. Also, some pear varieties are very easily damaged by abrasion (Valenciano García, 1990). Peeling or 'scuffing' of potatoes and other produce has been studied, and some testing devices exist to measure susceptibility to this type of damage on the skin (Muir *et al.*, 1990).

Cuts and punctures represent severe damage, caused by inappropriate equipment or handling; they are not related directly to fruit properties, and can be avoided by proper care of the equipment and of the handling systems.

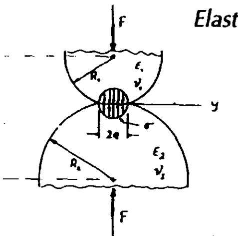
Measuring and modelling the contact phenomena

Contact models: applications

Various theoretical models have been used to explain and analyse the impact problem as applied to fruits. The first one was presented many years ago, and consists of considering a fruit as an elastic (generally spherical) body and applying the Hertz contact theory further developed by Shigley (Horsfield *et al.*, 1972; Rumsey and Fridley, 1977). This approach has been shown to be only approximately applicable, but has yielded much interesting information on many fruits, especially those we have called hard or rigid fruits. The elastic contact problem in fact describes the internal stresses and strains created in and below the contact area between fruit and impacter of elastic, rigid, isotropic and semi-infinite bodies. It states that bruising can initiate at a certain depth below the skin, where the maximum shear stresses and strains appear. Table 9.2 shows a summary of the most relevant mathematical relations of this model. At first it was mainly applied to peaches and pears, but later many applications have been and are being published on apples, and even plums, cherries, potatoes and many more (Chen *et al.*, 1984;

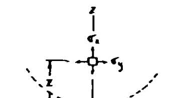
Table 9.2. Summary of the relevant features and mathematical relations of the elastic and of the viscoelastic models.

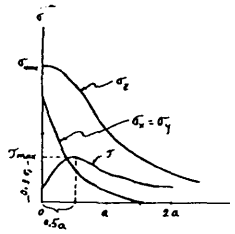
Elastic contact between two spheres



E_1 and E_2: elasticity moduli
ν_1 and ν_2: Poisson's ratios
F: force applied
a: radius of contact area
d: $(R_1 + R_2 - L)$ = deformation in the area of contact

$$d = \sqrt[3]{\frac{9\pi^2}{16} F^2 \left(\frac{1-\nu_1^2}{\pi E_1} + \frac{1-\nu_2^2}{\pi E_2}\right)^2 \left(\frac{1}{R_1} + \frac{1}{R_2}\right)}$$



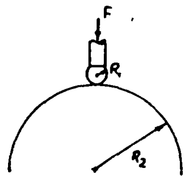


Inside the body

σ_z = principal stress, in the z direction
σ_y and σ_x = stresses in the y and x directions
z = depth
τ = shear stress

Stresses are a function of a, z, R_1, R_2, E_1, E_2, ν_1, ν_2 and their variation is shown for a selected fruit.

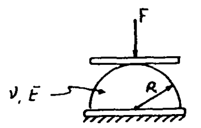
Particularization to spherical indenter



E_1 of intender → ∞ (steel much harder than fruit)
R_2 much larger than R_1

$$d = \sqrt[3]{\frac{9}{16}\,\frac{F^2}{R_1}\,\frac{(1-\nu_2^2)^2}{E_2^2}}$$

Particularization to flat plate



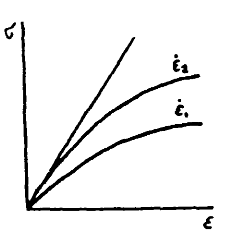
E_1 of flat plate → ∞
$R_1 = \infty$

$$d = \sqrt[3]{\frac{9}{16}\,\frac{F^2}{R_2}\,\frac{(1-\nu_2^2)^2}{E_2^2}}$$

Table 9.2 *Continued*

Viscoelasticity

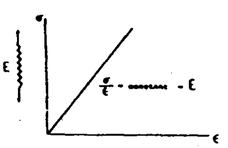
Combines elastic and viscous properties

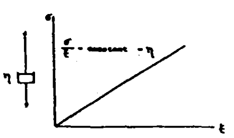


Deformation rate affects stress–strain relationship.

$$E = \frac{\sigma}{\epsilon} \text{ modulus of elasticity}$$

$\dot{\epsilon}_1$ and $\dot{\epsilon}_2$: strain rates, $\dot{\epsilon}_1$ being lower than $\dot{\epsilon}_2$





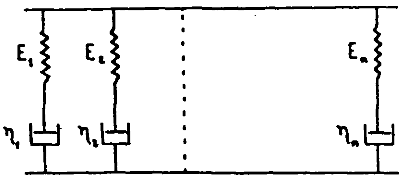
Spring and dashpot represent the elastic and viscous parts of biological tissues.

The *Maxwell model* combines both elements:

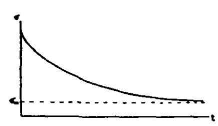
$$\dot{\epsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta}$$

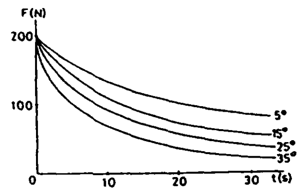
and its force–deformation relationship fits to the one shown by biological tissues.

Generalized Maxwell model is the sum of many Maxwell models.



Stress-relaxation test





For a given deformation applied to the product, *stress* (i.e. force) *relaxes* with time, in a characteristic way for each product and condition; a particular model can be thus fitted to each observed relaxation curve:

$$F(t) = \sum_{i=1}^{n} C_i\, e^{-\alpha_i t}$$

C_i and α_i are the characteristic constants.

EXAMPLE: Stress-relaxation curves are different for different temperatures in apples (Gil *et al.*, 1984).

Hemmat and Murfitt, 1987; García Alonso *et al.*, 1988; Lichtensteiger *et al.*, 1988; Blahovec, 1990; Sinn, 1990).

When studying different kinds of fruits and fruit-probes, in different maturity and turgidity stages, only very few show distinct shear failure

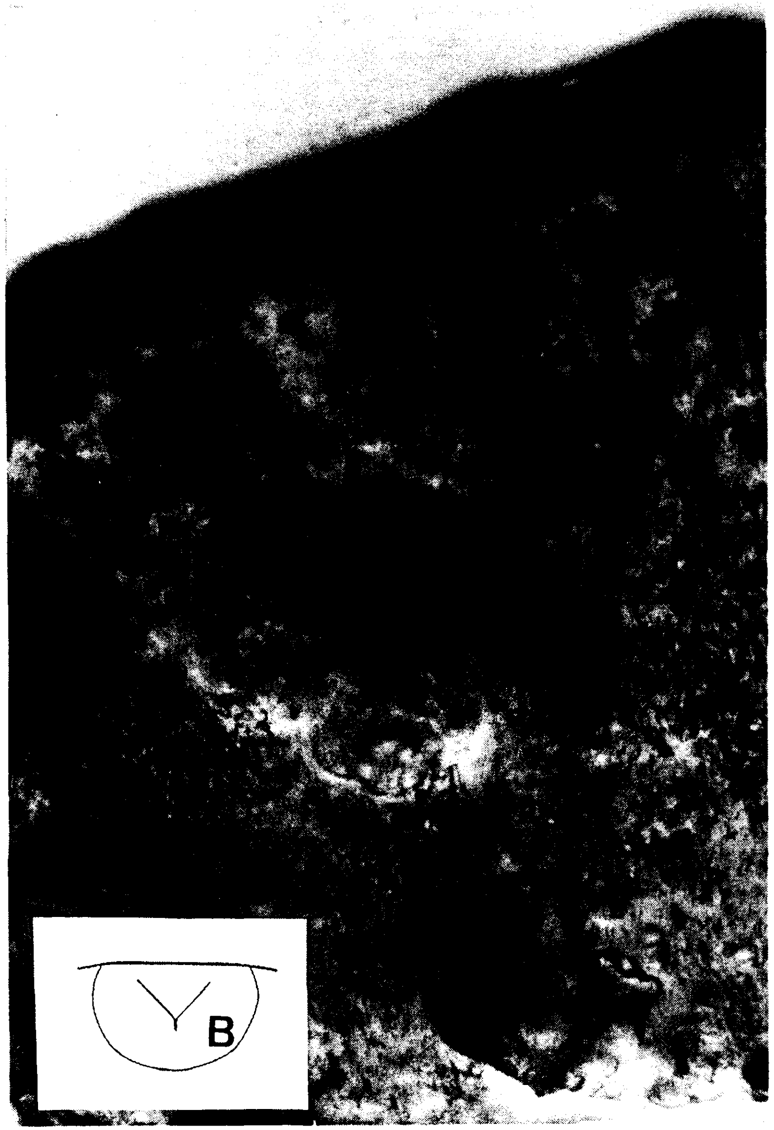


Fig. 9.2. Conical fracture (F) observed in pears (variety Limonera, 6 cm drop, 50 g sphere of 9 mm diameter); B: bruised tissue. (See also Fig. 9.7 (b).)

surfaces (conic, at 45° slope; see Fig. 9.2), and many show rather horizontal failure planes (especially apples: Jarimopas, 1984; Ruiz Altisent *et al.*, 1989; Fig. 9.3), other types of failure patterns, or no failure surfaces at all (Ruiz Altisent *et al.*, 1989).

Size of the observed bruised volume is not correlated to the calculated values of shear stress in many cases, especially when testing fruits at increasing maturity. This shows that the mechanical properties of fruits vary accordingly, and so do their impact responses; also, other physiological parameters of the fruit flesh are involved in the initiation and development of bruises (Rodriguez, 1988).

Impact parameters (especially mass, initial velocity, input energy, impulse, and radii of curvature) also affect greatly the impact phenomenon, as well as the macro- and microstructural properties of the fruits. Firmness of fruits is used as an index of maturity, and it is measured by puncture of the flesh. Discussion on the influence of firmness in bruising susceptibility of selected fruits is still open. On the basis of the elastic theory, a higher modulus of elasticity leads to higher stresses, and therefore higher bruising susceptibility should be observed; puncture firmness is generally correlated to modulus of elasticity. Common practice shows, however, that softer (less firm) fruits are usually more easily bruised during handling. In fact, puncture (Magness–Taylor) firmness is a complex test, combining different aspects of tissue strength, which vary in different ways with tissue properties.

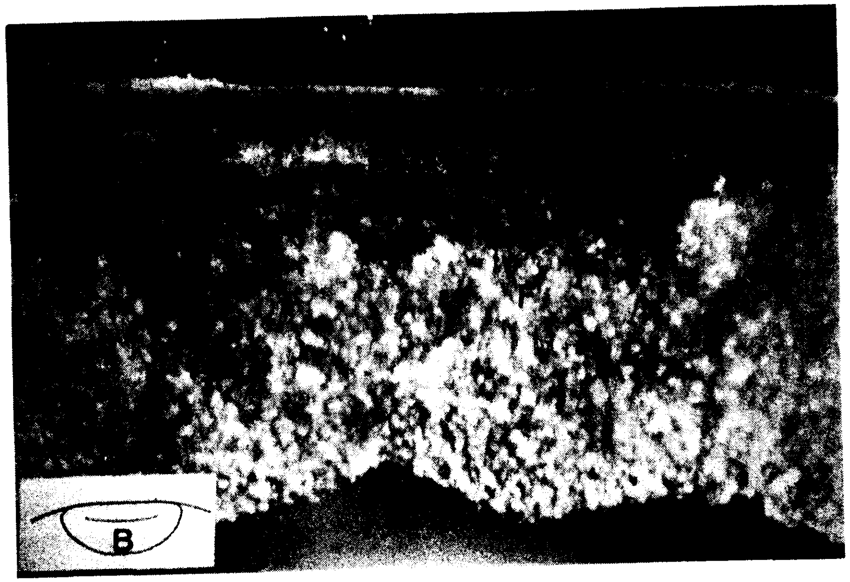


Fig. 9.3. Horizontal failure surface observed in apple bruises (Starking variety; B: bruised tissue; F: failure surface.)

Fruit tissue is made up by cells, their walls forming the rigid structure of the pulp; these cells are bonded together by a connecting substance, and the tissue contains varying proportions of gaseous spaces, free liquids or even oils (Pitt, 1982; Rodriguez *et al.*, 1990; Ruiz Altisent *et al.*, 1989; García Alonso *et al.*, 1988). Both cell walls and bonding material change greatly with ambient conditions and with ripening. Summing up, a fruit is in fact a physical body with continuously changing properties; and the response of fruits to contact loading is very much dependent on the type of loading.

Taking into account the viscous behaviour of the liquid fraction of fruit tissue, contact has also been modelled using viscoelastic models. Viscoelasticity has been extensively studied and applied to static testing of biological products (Rumsey and Fridley, 1977; Gil *et al.*, 1984; Gil, 1990). Hamann (1970) applied the viscoelastic model to the impact case, showing that stresses are distributed in the impacted tissue somewhat differently than when calculated by pure elasticity, but the applications shown do not significantly improve the elastic solution. Duration of impact is very low for fruits (5–8 ms; see below), whereas viscoelastic time constants are much longer (minutes). Rumsey and Fridley (1977) developed a finite-element analysis of contact stresses for elastic as well as for viscoelastic spherical bodies in contact, subjected to static load as well as to impact. By comparison of the distribution of stresses calculated by the analytical versus the finite-element procedures they concluded that for elastic homogeneous bodies no differences appear for both solutions. However, when material properties vary within the body, the finite-element method is the most appropriate for calculating internal stresses caused by static or impact loading (Fig. 9.4).

Gil *et al.* (1988) studied the effect of temperature and firmness differences on the viscoelastic modelling of the static stress-relaxation test of cylindrical probes of apple and pear flesh. Relaxation was significantly faster and larger for warmer and for less-firm samples, and size of bruises was observed to be smaller when impacting the corresponding fruits.

All these theoretical approaches for calculating internal stresses as a result of static contact and of impact, are only applicable for very small strains. Their application to problems where large strains occur, as is the case for most agricultural products, becomes questionable. Nevertheless, the description of the theoretical distribution of stresses and strains as a result of loading yields very useful information to be compared with empirical observations.

Testing devices

Testing devices which have been developed in recent years to apply and analyse controlled impacts to fruits include instrumented pendulums (Holt and Schoorl, 1984; Hughes and Grant, 1987), free-falling instrumented devices (Chen *et al.*, 1985), and spring-actuated falling rods (Gahtow, 1990).

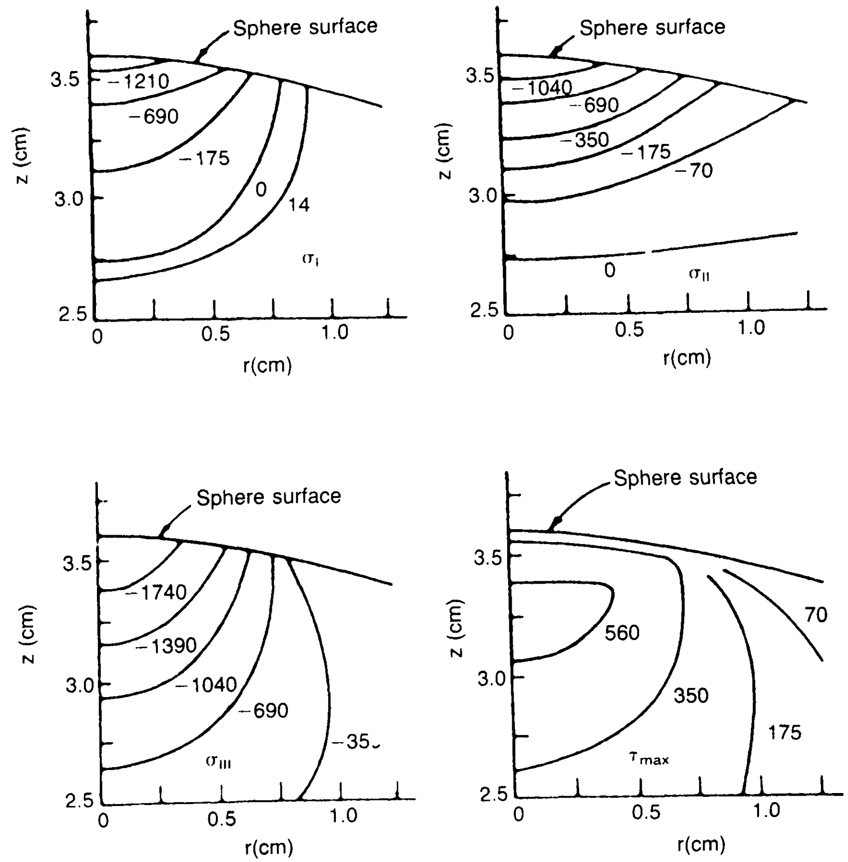


Fig. 9.4. Principal stresses (kPa) at time 16×10^{-3} seconds after a 5 cm drop as predicted by finite-element modelling of a viscoelastic sphere. The stress σ_I is the maximum principal stress and σ_{III} is the minimum principal stress, so that $\tau_{max} = (\sigma_I - \sigma_{III})/2$. (Rumsey and Fridley, 1977.)

Chen *et al.* (1987) and Garcia *et al.* (1988) used an impact testing device, consisting of a free-falling impacting rod with a changeable spherical tip, instrumented with a miniature accelerometer. The response of the sample to the applied impact can be fully characterized by the force/time curve obtained by each impact. Analysis of these impact curves has been the basis for various impact studies in fruits. Significant results were obtained, relative to the parameters which best characterize the impact response of these materials and to their correlation to fruit damage, variety and ripeness level of the fruits (Ruiz Altisent, 1990). Bruise damage, measured as the size and/or the volume of the affected fruit tissue is primarily related to input energy (that is, drop height) for a given variety in a given ripeness stage and physical

Table 9.3. Summary of impact parameters relevant to characterize impact response in fruits. First group are energy related parameters; second group are both related to energy of impact and to fruit texture; third group are significantly related to ripeness of fruits. (Selected apple and pear varieties; García Alonso *et al.*, 1988.)

Name of parameter	SI units	Symbol
Maximum deformation	mm	DM
Permanent deformation	mm	DP
Critical depth (maximum shear stress location Hertz model)	mm	PC
Maximum mechanical impulse	Ns	IM
Maximum bruise depth	mm	PM
Maximum bruise width	mm	AM
Percentage of rebound energy	%	%E
Maximum impact force	N	FM
Optimum slope force/time	N/s	F/T
Calculated coefficient	N^2/s	IF × F/T
Rebound velocity	m/s	VF
Total impact duration	ms	T
Final impact duration	ms	TF
Time to maximum force	ms	TM
Increment TT–TF	ms	IT
Optimum slope force/deformation	N/m	FD
Apparent dynamic modulus of elasticity	Pa	ME
Maximum shear stress	Pa	EC

condition. The relevant impact response parameters are maximum deformation (DM), permanent deformation (DP), maximum impulse (IM), maximum impact force (FM) and impact duration (T). A correspondence factorial analysis is applied, to group the most significant parameters on the basis of their linear relation to: (i) input energy; or (ii) ripeness level. Table 9.3 shows all the relevant parameters and the groupings resulting from the described tests.

With this empirical approach of impact study and analysis, parameters of different origin can be combined and analysed jointly: (i) measured parameters; (ii) parameters calculated from the acceleration data; and (iii) parameters calculated from the theoretical models. In tests carried out on four varieties of Asian pears (Chen *et al.*, 1987), significant effects of variety, time in cold storage, and time of ripening in 20 °C room, were observed on impact and compression bruise sizes, and on most of the impact parameters. Correlations were established between bruise dimensions and some impact response parameters. Firmness appeared always negatively correlated to bruise dimensions.

Rodriguez and Ruiz (1989) applied linear regression models to the impact response parameters in pears of the Blanquilla variety, trying to explain bruise size, defined by its depth and diameter. The included parameters were: maximum impact force, maximum impact deformation, permanent deformation, input energy, absorbed energy, impact duration, firmness, acidity, soluble solids and the soluble solids / acidity ratio. Around 57% of the total variation could be explained by these parameters, being most of the variation explained by input energy alone; when fruits were in the senescent stage (ripe to overripe), deformations (maximum and permanent) were the most relevant parameters in explaining bruise size. Pears change very significantly from rigid to plastic with advancing maturity.

Bruise volume has been used by various researchers rather than depth and diameter to evaluate bruise severity; Kampp and Nissen (1990) studied the susceptibility to impact, applied by an instrumented pendulum, of seven varieties of apples. As in the results reported by many other researchers, high correlations were found between input energy (E_{abs}) and bruise volume (V) for any of the three (early, mid- and late harvest) samples of each variety. The important result was, however, that expressing the impact susceptibility as the regression coefficient a in the expression:

$$\boxed{V = aE_{abs} + b \quad (a \text{ in ml/J; } b \text{ in ml})} \qquad [9.1]$$

The impact susceptibility is different for every sample of every variety. From this and many other similar results it is concluded that neither input nor

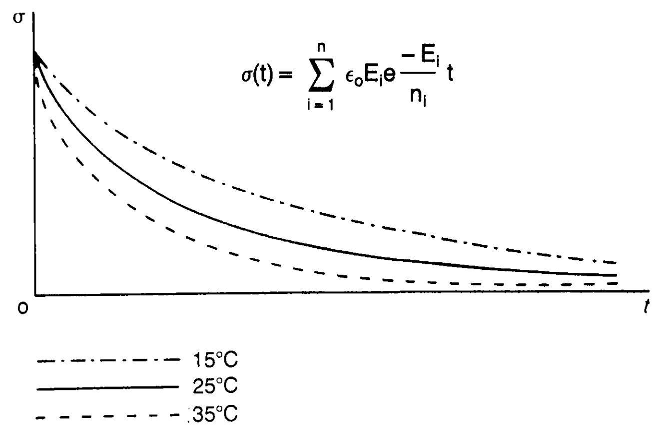


Fig. 9.5. Stress-relaxation curves of cylindrical probes of apple flesh, at different temperatures, for equal initial stress values (Gil *et al.*, 1988; Gil, 1990). Stress-relaxation was observed to be faster and larger for warmer apple tissue. The variation of stress with time at constant deformation is modelled by a three- or four-elements Maxwell model, where ϵ_0 = initial strain, E_i = elastic constants and n_i = viscous constants.

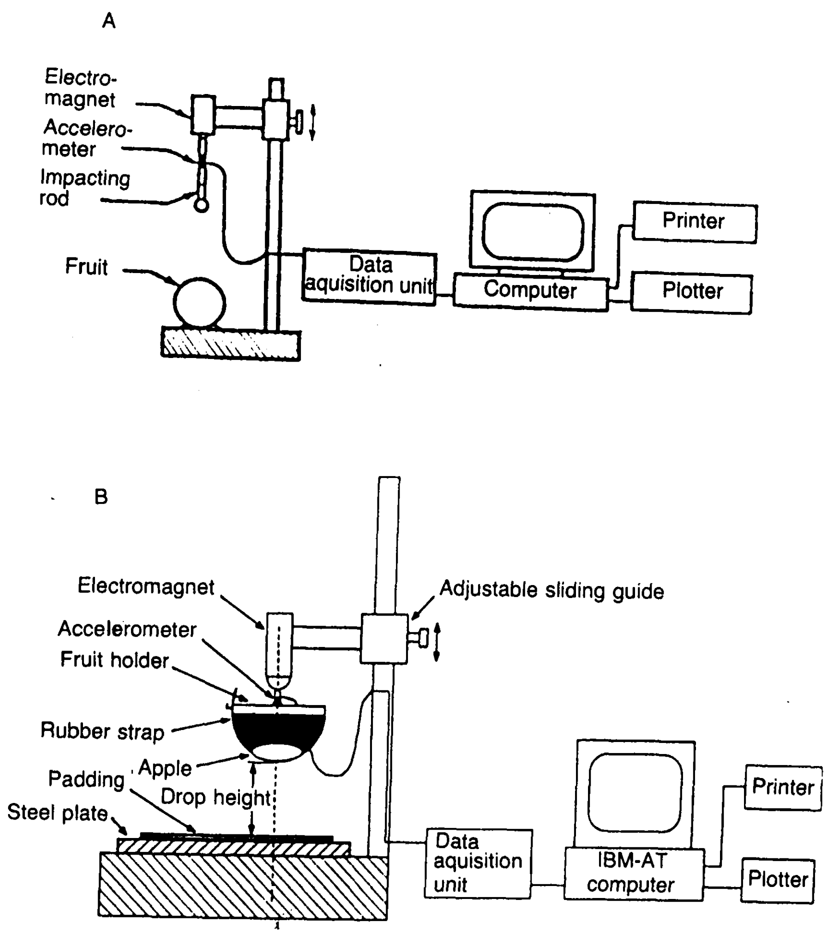


Fig. 9.6. Impact testing devices and associated instrumentation: (A) Dropping steel sphere on fruit; (B) dropping fruit on steel plate and padding materials. (Chen *et al.*, 1985; Chen and Yazdani, 1989.)

absorbed energy are in themselves sufficient to predict impact sensitivity of apples and consequently of other fruits. Other parameters related to: (i) the impact process; (ii) the response of the fruit due to its physical properties; and (iii) the structure and physiology of the fruit, must be included to explain bruising.

Free fall of instrumented fruits was used by Chen and Yazdani (1989; see Fig. 9.6). The degree of bruising of Golden Delicious apples dropped from different heights onto different impacting surfaces (padded differently) could be predicted by multiple regression models based on: (i) measured and calculated impact parameters; and (ii) Fourier-Transform coefficients of

the impact acceleration curves. The relevant parameters were maximum value of force/time rate change (F/T slope), maximum deformation (DM), and absorbed energy (EAB); further, maximum force (FM) and duration or time of impact (T) were significant in the regression equation. These results are basically coincident with those obtained by other researchers already mentioned.

Siyami *et al.* (1988) used an impact table to perform free fall tests on apples. Application of the elastic contact model was used to develop an equation for predicting bruise diameter: BD = Function (W = apple weight, H = drop height, D = apple diameter and F = Magness–Taylor firmness). A multiple linear regression model, based on the parameters apple diameter, Magness–Taylor force, maximum acceleration, and total velocity change (v–v rebound), could accurately predict bruise diameter in Ida Red apples. The theoretical solutions of the elastic model, as well as a similar one developed including plastic deformation, both underestimated bruise diameter in these fruits. These results show again that, using the appropriate measuring instrumentation, empirical models based on measured and, eventually, calculated parameters are appropriate for studying impact response and for predicting bruise size.

Lichtensteiger *et al.* (1988) used a drop-testing apparatus where the samples were released from specific heights onto a rigid aluminium plate instrumented with a force transducer. Various types of models (fabricated balls) and red tomatoes were tested. Changing the properties of the shell in relation to the internal material of the tested balls showed that the shell effect is prevalent when the internal structure is softer than a relatively thin shell. When the internal material is stiffer than the shell, no shell effect was observed. This result shows that the effect of the skin when testing hard or soft fruits is in fact relevant in the response to impacts, and it will be different for changing ripeness of the fruits.

Brusewitz and Bartsch (1989) also used dropping of fruits (five varieties of apples) onto a plate, instrumented with a piezoelectric force transducer. They showed that the relation ‘bruise volume / absorbed energy’ changes gradually with storage time, decreasing, and consequently also with firmness. Other references show different or opposite results (Hung and Prussia, 1988; Holt and Schoorl, 1984), namely an increase in ‘bruise volume / absorbed energy’ when reducing firmness. They also found that impact contact time (T) was closely correlated with decreasing firmness, as well as the relation impact force / contact time (FM/T), very much in agreement with all the impact parameters research results found so far.

Timm *et al.* (1989) studied impact susceptibility in apples. Fruits were dropped onto an impact surface, carrying an accelerometer on the opposite side. Multiple linear regression based on similar parameters as the ones reported by Siyami *et al.* (1988) were very good predictors for bruise dimensions, on both hard and padded surfaces.

Sinn (1990) performed free-fall impact testing of cherries and plums. The stress–strain behaviour of soft fruits is not like the one shown by hard fruits, but a good correlation was observed between impact force and fruit damage. Fruits were dropped onto a plate instrumented with a force transducer. Data were gathered on the relative effect of different padding materials on the maximum force (FM) determined at impact.

Bruising can also be caused by static and quasi-static contact loading. All the mechanical models which have been applied to describe impact were developed for static contact, with similar results and with the same restrictions for accuracy. Viscoelasticity becomes important in static loading. Its main effect is that instantaneously applied stress relaxes with time, and instantaneous strain 'creeps' with time; the resulting stresses are therefore lower than in impact, for similar energy inputs, and the strains larger. Chen *et al.* (1987, cited above) compared the bruises produced by compression and by impact, and they observed that bruise pattern could be very different in both loading speeds: for a variety of pears, long spikes extended radially from the impact area into the fruit, showing that loading rate has a great influence when analysing strength and failure of fruits. Results obtained so far indicate that higher loading rates and higher firmness (hardness) of fruits usually show shear failure patterns; slower loading rates and lower firmness show normal stress or strain failure (Chen and Sun, 1984, Ruiz Altisent *et al.*, 1989). Therefore, discrepancies found in the results of different researchers in relation to fruit tissue failure should be due to these mentioned differences in loading rate and fruit properties in their testing procedures. This refers also to the bruise volume / energy ratio discrepancies, discussed earlier.

In electron microscope studies carried out in a variety of apples (see below), it was observed that degradation of cells was different when impacted than when slowly compressed.

Structure of bruises

Closer observation of bruises caused by impact shows that different species of fruits (Rodriguez, 1988; Ruiz Altisent *et al.*, 1989; Rodriguez *et al.*, 1990, studying apple and pear fruits) show different bruise sizes and patterns which appear in the absence of any significant variation in other relevant parameters (like radii of curvature of the fruits or the impacters, or the energy of impact). Therefore, they have to be related to structural differences between these fruits, which in fact are very important. These include size and shape of cells in hypodermis (first cell layers below the skin) and pulp, and the presence of intercellular spaces. Table 9.4 includes the most important differences in the structure of the fruit tissues, gathered for apples and pears. Figure 9.7 shows different models of average bruises observed in the varieties studied. The differences between them affect the following.

Table 9.4. Differences in tissue structure between apples and pears. (Ruiz-Altisent *et al.*, 1989.)

Apple	Pear
Epidermis (skin)	
Squared cells	Flat cells
Many void spaces	No void spaces
Suberized cells	
Thin-walled hairs	Thick-walled hairs
Hypodermis (below skin)	
Isodiametric cells of variable size	Polygonal cells with thick walls
Large intercellular spaces	Few, small intercellular spaces
Parenchima (flesh)	
Large, irregular cells	Polyhedric cells of smaller size
More and larger intercellular spaces	Esclereids: thick-walled cells in groups
Many fibres	Calcium oxalate (hard) crystals
Lower apparent density	Higher apparent density

1. The relation depth/width, significantly higher in pears than in apples. For 12 cm drops (0.06 J), the average depth is similar for both apple varieties (Golden Delicious and Starking) and for two of the pear varieties (Decana and Blanquilla) – that is, 2.5–3.5 mm, with no significant change for an 11-week period of cold storage; however, bruise width is significantly larger (7–8 mm) for both varieties of apples (pears 3–5 mm). The larger and more numerous intercellular spaces present in apple tissue cause transversal failure surfaces, which are able to absorb much of the strain during impacter penetration, thus dissipating much of the stresses and preventing the formation of deep bruises.

2. The size, shape and number of fractures observed inside the bruised tissue. Close observation of the bruises makes it possible to identify the presence of discontinuities, eventually fractures, in what may be the maximum stress/strain location in the bruised area when impacted. They always appear some millimetres below the skin, and centred in the bruise itself. In the case of apple varieties, somewhat curved horizontal fissures appear (see also Jarimopas, 1984), not completely separated but rather showing cell walls like bridges between both sides; the cells are crushed together, with no evidence of having slid, so they may not be properly considered fractures. On the other hand, in the case of Decana pears, real conical and vertical fractures are observed (Fig. 9.8), suggesting stress failure as described for some fragile materials. This type of fracture has been described previously in Asian pears (Chen *et al.*, 1987).

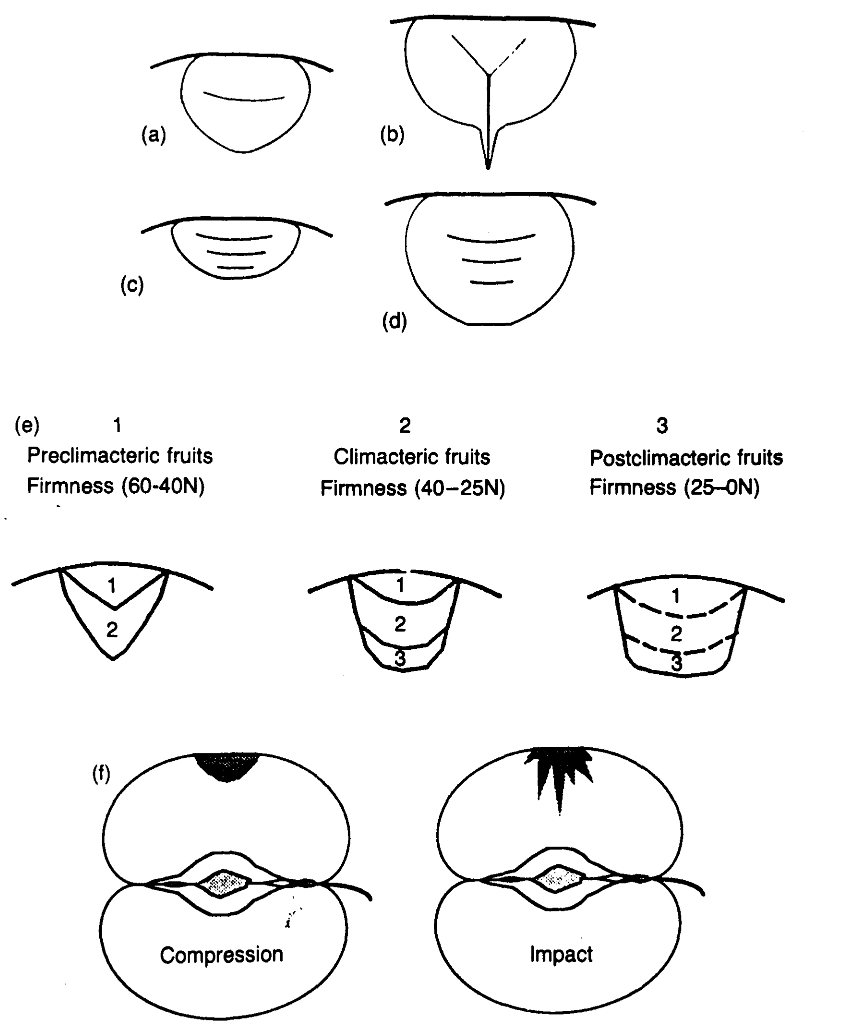


Fig. 9.7. Types of bruises and fractures or fissures observed in varieties of apples and pears (12 cm drops): (a) Limonera pear; (b) Decana pear; (c) Golden Delicious and Starking apples; (d) and (e) Blanquilla pear (1 hard, 2 ripe, 3 soft); (f) comparison of compression and impact bruise patterns in Asian pears.

3. For low-energy impacts, although a bruise appears (of smaller size) no discontinuity is observed.
4. It is important to note that after some time, the totality of the stressed tissue becomes discoloured, not only the ruptured spot or surface. It is also observed that the specific reactives for polyphenoloxidase activity become

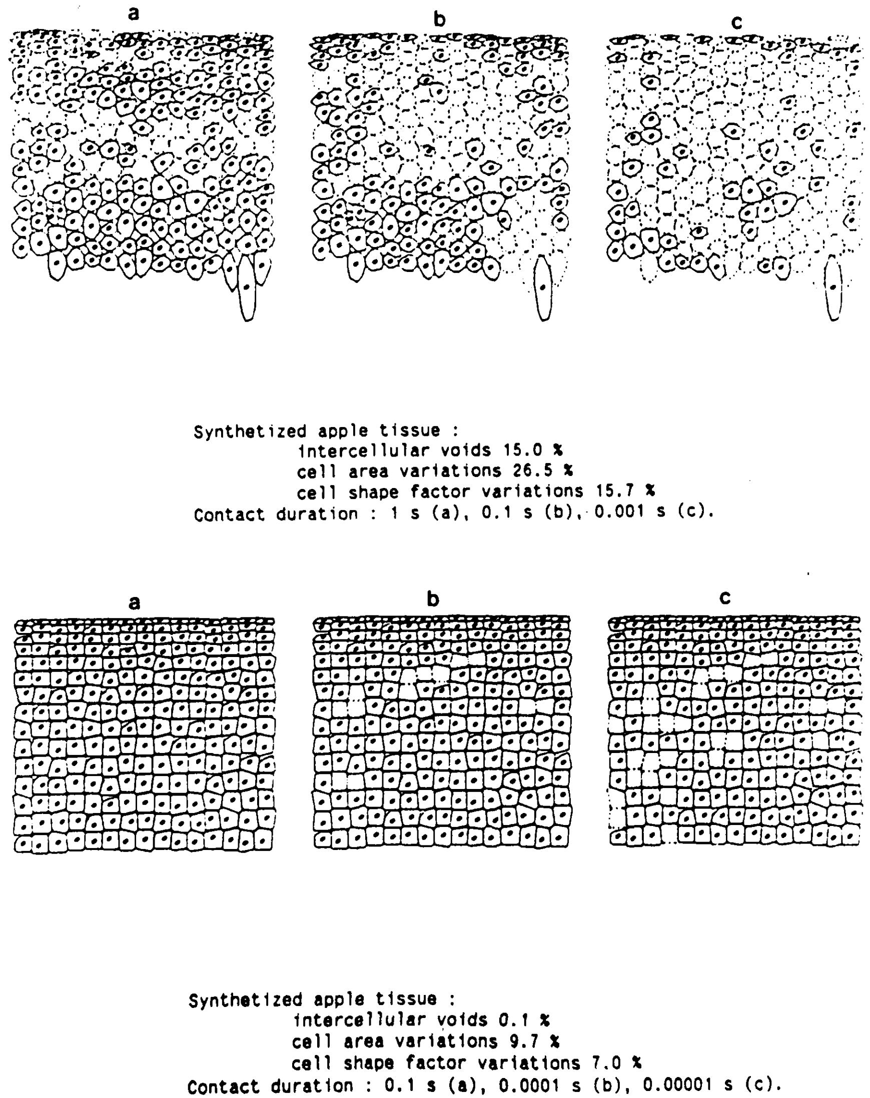


Fig. 9.8. Mathematical graphical representation of apple tissues of different structure. Simulation of contact durations: 1 to 10^{-3} seconds for the 'soft' tissue (top); 0.1 to 10^{-5} seconds for the 'packed', hard tissue (bottom). (Roudot and Duprat, 1990.)

active in the total affected area (Rodriguez, 1988), very clearly delimiting the tissue that has been damaged.

Rodriguez *et al.* (1990) made transmission electron-microscope studies in Granny Smith apples, showing that after a few hours, cells of the bruised area are altered, with intensive vesiculation, either in the vacuole (inside the cell) or in the middle lamella region between adjacent cells. It was observed that cell wall rupture is not necessary to initiate bruise reactions; if it occurs, it may additionally leak the altered compounds out of the cells to the intercellular spaces. Thus, the browning reaction in fruit under applied loads can take place either outside or inside the cell. Low stresses applied to tissue cells which cause no rupture of cell walls, cause bruising, developed internally in the cells.

Roudot and Duprat (1990) used a graphical model to simulate the effect of these structural differences on failure in apple flesh. The model starts considering that apple flesh is not homogeneous and that it contains a variable proportion of intercellular spaces. With a special two-dimensional tessellation model of the cellular tissue it was possible to simulate the collapse of cells as a result of varying levels of loading, time of application (1, 0.1 or 0.001 seconds), percentage of intercellular voids and cell-covered surface, and of a factor describing the shape of the cells. Very different failure patterns could be obtained and compared to real bruises. Interesting observations were made, showing that collapsed cells increase with void space percentage and hetereogeneity in cell size and shape increases.

Biological variables

As has been stated already, the properties of fruits change in relation to many biological variables. These influences begin in the early stages of development of the fruit on the plant, caused by variations in varietal, agronomic and climatic conditions, and continue throughout the whole growing season. Some attempts have been carried out to explain the influence of such variables in the susceptibility of fruits to mechanical damage.

Johnson and Dover (1990) studied some factors influencing the bruising susceptibility of a variety of apples (Bramley's Seedling). Fruits from 24 commercial orchards were tested during six seasons. It was observed that bruising susceptibility (measured by means of an instrumented pendulum, applying 0.19 J of impact input energy) varies in a greater measure within a season (between orchards) than between seasons. There was no evidence of any agronomic or microclimatic factors which might be responsible for such differences – neither soil management systems (complete grass covering, strip-herbicide or overall herbicide), nor nitrogen fertilizer applications or mineral composition of leaves or fruits. Bruise volume was negatively correlated to fruit firmness (Magness–Taylor puncture test). Also, larger fruits were observed to be more susceptible to bruising, within samples of the same orchard; cells of such fruits are larger as well as their intercellular spaces. Water loss appeared to increase bruising resistance to the fruits. Bruise volume increased significantly with picking date, as shown in Fig. 9.9.

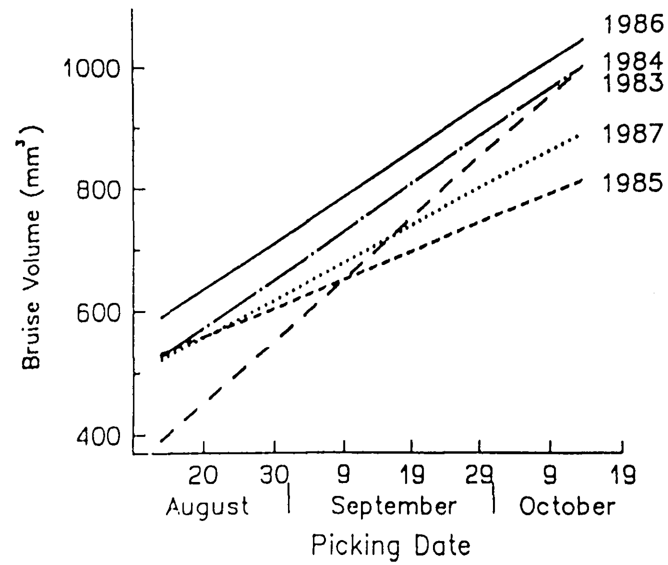


Fig. 9.9. Regression lines relating bruise volume to harvest date for Bramley's Seedling apples (impact energy 0.19 J). (Johnson and Dover, 1990.)

Hatfield and Knee (1988), Pitt (1982), Pitt and Davis (1984) (cited in Johnson and Dover) and other authors have associated turgor pressure with a reduction in the strength of apple tissue. Water loss appeared to increase bruising resistance of the fruits studied by the cited authors.

Jaren and Recasens (1990) tested the effect of calcium treatments on the physical properties of apples. Many researchers have observed an increase of tissue firmness when treated with calcium. This element contributes to maintaining cell membrane and cell wall integrity. Samples of Golden Delicious apples were treated with different calcium solutions, weeks before harvest. Static and impact tests were applied to the fruits, after harvest and after various intervals of cold storage. Significant differences were observed in the firmness of fruits subjected to some of the calcium treatments, as well as a reduction in bruising susceptibility.

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